High Frequency Interconnects on Silicon Substrates

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ABSTRACT

The measured propagation constant of coplanar waveguide (CPW) on silicon wafers as a function of the line dimensions and the resistivity of the Si wafer; CPW on GaAs wafers as a function of the line dimensions; and thin film microstrip (TFMS) fabricated with polyimide on the surface of a silicon wafer is presented. It is shown that the attenuation of CPW on 2500 Ω-cm Si wafers and of TFMS with a polyimide thickness of 4 μm or greater is comparable to the attenuation of similar lines on GaAs.

INTRODUCTION

The increasing demand for low cost, microwave and millimeter-wave integrated circuits has spurred the development of Si MMICs. These circuits can be fabricated using standard Si integrated circuit manufacturing processes, and thus utilize the much larger Si manufacturing base that is available compared to the GaAs and InP manufacturing base. Furthermore, integration of digital control and data processing circuits with microwave circuits is possible to lower the integration and packaging costs and improve the overall system reliability.

To overcome the high attenuation and coupling between microwave transmission lines that occurs when standard CMOS grade Si wafers with resistivities of a few Ω-cm are used, novel microwave interconnect techniques are required. One option is to use high resistivity Si (HRS) wafers that are readily available with resistivities above 3000 Ω-cm for less than $20 per wafer. The HRS wafers not only permit transmission lines to be built directly on the Si substrate in the same manner as they are in GaAs circuits (shown in Figure 1) but also improves the isolation between components [1,2]. A second alternative is to use standard Si wafers with a top side metal ground plane on which TFMS lines are fabricated using either polyimides, SiO_2, or other dielectrics as shown in Figure 2 [3,4].

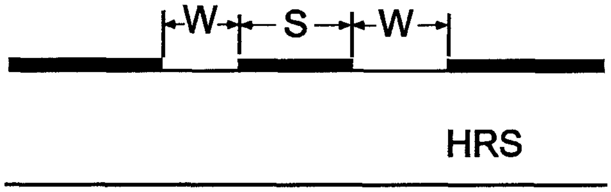

Figure 1: Coplanar waveguide on high resistivity Si (HRS).

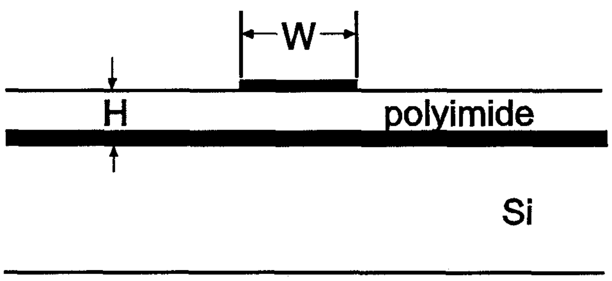

Figure 2: Thin film microstrip with polyimide substrate fabricated on Si wafer.

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In this paper, the measured characteristics of coplanar waveguide on high resistivity Si and of TFMS is compared to the measured characteristics of CPW on GaAs. From the measured attenuation constant, design guidelines are presented to aid in the choice of the best interconnect technology on Si wafers.

MEASUREMENT PROCEDURES

CPW lines are fabricated on Si wafers with resistivities of 400 and 2500 Ω-cm, ε_r=11.9, and a nominal thickness of 410 μm and on GaAs wafers with ε_r=12.85 and a thickness of 375 μm. Prior to fabrication, all wafers are thoroughly cleaned and the Si wafers are HF dipped to remove any native oxide that had formed. The metal patterns are defined through a liftoff process and consist of 0.02 μm of Ti and 1.45 μm Au. No insulators, SiO_2 or Si_3N_4, are grown on the wafers and there are no back side ground planes. Coplanar waveguides with S and W of 10 and 9 μm and 80 and 51 μm respectively were fabricated. Both of these lines have a nominal characteristic impedance of 50 Ω.

The thin film microstrip lines are fabricated on standard 3 Ω-cm Si wafers that serve as a carrier for microwave interconnects. The microstrip ground plane consists of 0.02 μm of Ti and 2.5 μm Au evaporated onto the Si wafer. Over this, DuPont adhesion promoter and PI-2611 polyimide which has a relative dielectric constant of 3.12 and a loss tangent of 0.002 is spun on in a single layer and cured. To open holes in the polyimide for probe pads, spin on glass and photoresist are used as a mask and the holes are reactive ion etched. Finally, the via holes are filled and the microstrip lines are defined in a single liftoff step. The microstrip lines consist of 0.02 μm of Ti and 1.3 μm Au. Microstrip lines with a polyimide thickness of 2.45, 4.35, 5.90, and 7.40 μm and a strip width of 5.0, 9.5, 12.5, and 16.5 μm respectively are characterized. Each of these lines have a nominal characteristic impedance of 50 Ω.

To measure the complex propagation constant of each line, an HP 8510C vector network analyzer, Cascade probe station, and GGB Industries picoprobes are used. A quartz spacer is used between the semiconductor wafer and the metal wafer chuck of the probe station to eliminate microstrip mode coupling when characterizing the coplanar waveguide. The line characteristics are determined through a TRL calibration routine implemented by MULTICAL [5]. Besides the thru line, four delay lines are used with the longest being 1 cm longer than the thru line. Although MULTICAL uses the measured characteristics of each line at every frequency point through a weighted averaging routine, the accuracy of the results is further enhanced by repeating each set of measurements three times and averaging the results.

RESULTS

While designing microwave circuits, the attenuation of the interconnect lines must be reduced to maintain high gain and low noise figure. Attenuation of transmission lines may be expressed in different formats. For circuit interconnects and power distribution networks, the attenuation relative to a physical line length (dB/cm) is most appropriate. Whereas for matching circuits, it is most appropriate to express attenuation relative to the guide wavelength (dB/λg).

First, the attenuation per unit length of a very narrow CPW, a very wide CPW, and a thin film microstrip structure is shown in Figures 3-5, respectively. Comparing the CPW lines on Si and GaAs, it is seen that the attenuation is high for moderate resistivity Si, but the attenuation of CPW on 2500 Ω-cm Si is approximately the same as that of similar lines on GaAs which agrees with past observations [6]. Furthermore, for the narrow CPW line, the attenuation of the 2500 Ω-cm Si line is lower than the GaAs line above 6 GHz. This has also been observed by Reyes [7], but since this inversion in the attenuation plots is not seen in the wider CPW line shown in Figure 4, further characterization is required to verify and explain this. The attenuation of the TFMS line shown in Figure 5 is comparable to the attenuation of the similarly sized narrow CPW line when the polyimide thickness is small, and it is lower than the CPW attenuation on GaAs when the polyimide thickness is greater than 3 μm.

By using the measured effective permittivity of the transmission lines, the attenuation per wavelength can be determined. This is shown in Figures 6-8 for the narrow CPW line, the wide CPW line and the TFMS lines, respectively. It is first noted that in Figures 6 and 7, the attenuation of the CPW lines on GaAs is lower than the attenuation on Si across the entire frequency band. It is further seen though that the attenuation of the CPW on 2500 Ω-cm Si is approximately the same as the same line on GaAs. Comparing the attenuation of the TFMS lines shown in Figure 8 to the attenuation of the narrow CPW lines, it is seen that the TFMS lines have a higher attenuation per wavelength. This is due to the lower effective permittivity of the TFMS lines.

CONCLUSIONS

In this paper, it is shown that microwave transmission lines on Si wafers can have attenuation comparable to that of lines on GaAs substrates. In fact, for similarly sized transmission lines, the attenuation per unit length of TFMS lines can be lower than the attenuation of CPW on GaAs. Therefore, for distribution networks, TFMS on Si is a good alternative to increasing the CPW line width. If the transmission lines are to be used for matching networks though and the attenuation per guided wavelength is more critical, CPW on high resistivity Si is a better alternative.

ACKNOWLEDGMENTS

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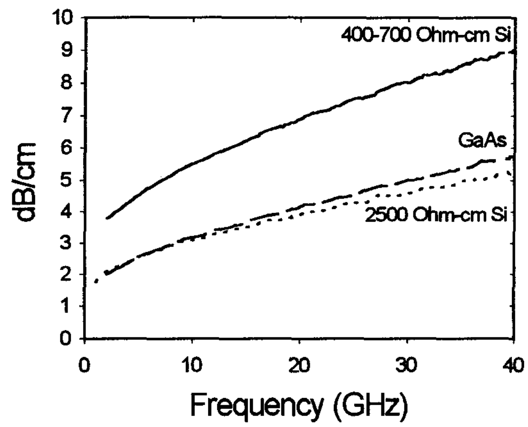

Figure 3: Measured attenuation per length of CPW lines with S=10 and W=9 micron.

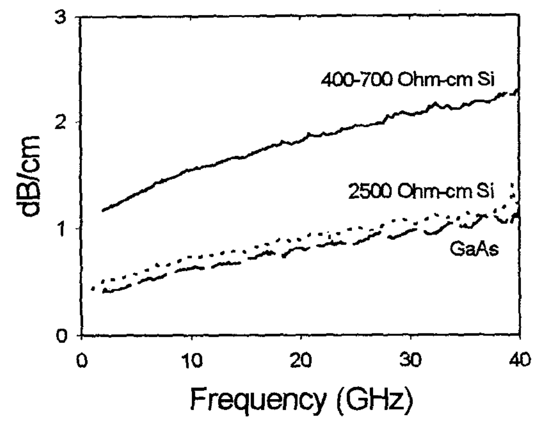

Figure 4: Measured attenuation per length of CPW lines with S=80 and W=51 micron.

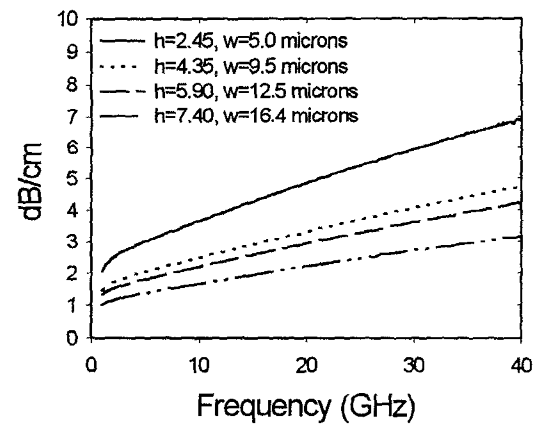

Figure 5: Measured attenuation per length of thin film microstrip lines.

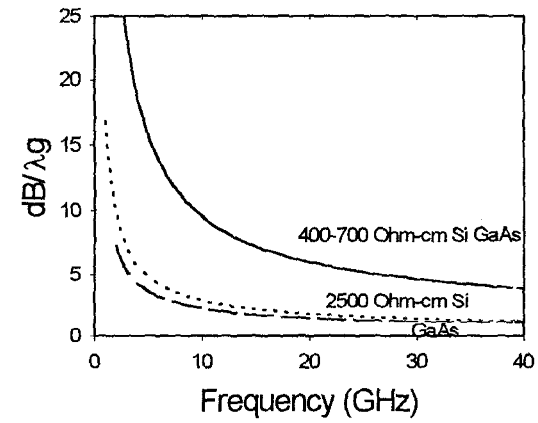

Figure 6: Measured attenuation per guided wavelength for CPW lines with S=10 and W=9 micron.

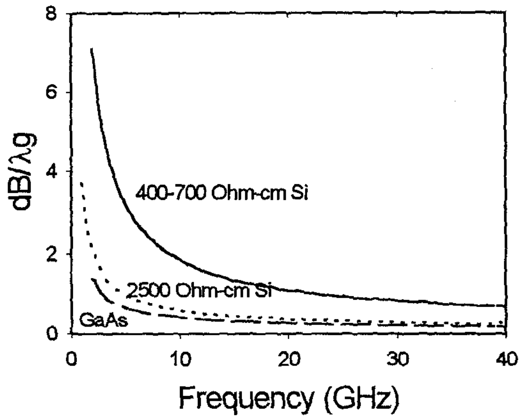

Figure 7: Measured attenuation per guided wavelength for CPW with S=80 and W=51 micron.

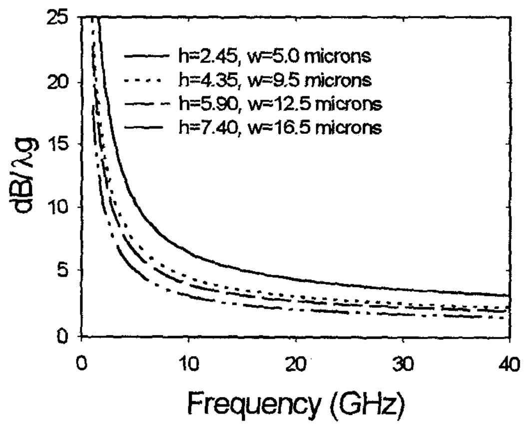

Figure 8: Measured attenuation per guided wavelength of thin film microstrip.